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The Secondary and Tertiary Particles Produced by Cosmic Rays

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Cosmic-ray secondaries and tertiaries have been studied in a series of experiments. It has been shown that the secondaries from lead have little power to produce detectable tertiaries or showers from lead or aluminum. The secondaries from aluminum have been found to produce more showers in lead than the secondaries from air. The absorption coefficient of the secondaries from aluminum has been found to be 0.7 cm^{-1} Pb and the absorption coefficient of their lead tertiaries 2.0 cm^{-1} Pb. The values for secondaries from air and a heavy roof, and their lead tertiaries were previously found to be 0.5 cm^{-1} Pb and 2.58 cm^{-1} Pb. The values obtained from Rossi's and Funfer's data are 0.32 cm^{-1} Pb for the air secondaries and 1.18 cm^{-1} Pb for their lead tertiaries. It follows that the air secondaries and their lead tertiaries have greater energies than the aluminum secondaries and their lead tertiaries. It has been found that a component of the cosmic rays even softer than the corpuscular component is probably the chief source of the secondaries producing the showers. There is some evidence that non-ionizing particles produce a portion of the showers and that possibly non-ionizing secondaries are produced in lead and that these particles can produce ionizing particles in aluminum.

THIS paper contains an account of experiments on the production and absorption of cosmic-ray secondary and tertiary particles. It follows the work of a previous paper.[1] The results of these new experiments and those of other workers, B. Rossi,[2] Funfer,[3] Ackemann[4] and Hummel,[5] help to confirm the assumptions made and the theory proposed in the previous paper.

If we place an absorbing layer of lead in the path of the cosmic-ray primaries and secondaries, we obtain tertiary rays produced by the absorption of the secondaries. At the same time the primary cosmic rays produce secondary particles in the lead. These lead secondary particles are strongly absorbed. After a certain thickness their number reaches a constant ratio with the number of primaries.

[1] J. H. Sawyer, Jr., Phys. Rev. **44**, 241 (1933).
[2] B. Rossi, Zeits. f. Physik **82**, 151 (1933).
[3] E. Funfer, Zeits. f. Physik **83**, 92 (1933).
[4] F. Ackemann, Naturwiss. **22**, 169 (1934).
[5] R. M. Hummel, Naturwiss. **22**, 170 (1934).

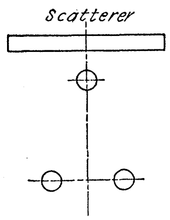
In the previous paper the number of tertiary particles ejected by cosmic-ray secondaries from an absorbing layer was shown to be given by the equation

$$\bar{n}_t = K\mu_s e^{-\mu_s l}\left[\frac{1-e^{-l(\mu_t-\mu_s)}}{\mu_t-\mu_s}\right]. \qquad (1)$$

Here n_t is the number of tertiaries emerging from the bottom of a layer of thickness, l, K is a constant, μ_s is the absorption coefficient of the secondaries, and μ_t is the absorption coefficient of the tertiaries. A similar result was obtained at the same time by Bhabha.[6]

The violent bursts of ejected particles, Hoffmann Stösse, produce triple coincidences in the usual arrangement shown in Fig. 1. The Stösse, however, are rare events in comparison with the frequent production of tertiary particles. Messerschmidt[7] has shown that the number of Stösse per

[6] H. J. Bhabha, Zeits. f. Physik **86**, 190 (1933).
[7] W. Messerschmidt, Physik. Zeits. **34**, 897 (1933).



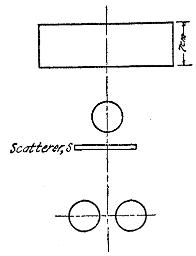


FIG. 1. FIG. 2.

FIG. 1. Diagram of usual cosmic-ray apparatus for investigating showers.

FIG. 2. Arrangement for investigating lead secondaries.

hour from a large mass of material is only about 0.5 to 1.0. This is certainly small in comparison with the production of tertiaries at a rate usually as high as 10 or more per hour. Also the number of Stösse is roughly proportional to the amount of material present, hence in the present experiments, where usually small amounts of absorbers are used, the number of Stösse is much smaller than 0.5 to 1 per hour and so the Stösse can be neglected.

The lead secondaries are assumed to be projected in an almost straight-ahead direction so that they could not produce triple coincidences in a counter arrangement similar to Fig. 1. This assumption was experimentally verified in (1). A beam was defined by two counters and a search with a third counter was made for secondaries produced in a large lead block. No secondaries were found at any angle hence they must have been projected in a straight-ahead beam. We neglected in (1) the possibility that these secondaries of the absorbing material might produce a portion of the tertiary particles by their absorption in the same material. In most experiments the absorbing material is lead so we have made an experimental test for lead tertiaries produced by lead secondaries.

The apparatus used in these experiments is essentially the same as that used in (1). The three Geiger counters are 4.8 cm in diameter and 20 cm effective length. They contain argon at 3 cm pressure and operate at about 2000 volts. They are connected to the usual selecting amplifier with a thyratron counting circuit.

The arrangement of Fig. 2 was used for this test for lead tertiaries produced by lead secondaries. A large block of lead 7 cm thick, 14 cm wide and 40 cm long above the counters cut out the air secondaries in the solid angle defined by the counters and replaced them with lead secondaries. These pass through the top counter and fall on the scattering layer S where they are absorbed with the production of tertiaries.

With this arrangement, counts were made with the lead block in and with or without the scattering layer S. A count was also made with S in and the block removed so that the air secondaries produced tertiaries in S. From the results shown in Table I, we see that the tertiaries

TABLE I.

S	0.63 cm Pb	0.16 cm Pb	0.63 cm Al	0.32 cm Al
Counting Rate with Pb Block and S	4.10 ± 0.17	3.5 ± 0.25	4.3 ± 0.20	4.4 ± 0.21
Counting Rate with Pb Block Alone	4.02 ± 0.19	3.3 ± 0.20	4.2 ± 0.18	4.5 ± 0.22
Counting Rate with S Alone	6.94 ± 0.24	4.76 ± 0.18	4.33 ± 0.20	4.7 ± 0.17

produced in S by the lead secondaries do not affect the count.

The lead secondaries have lower energy than light element secondaries and their lead tertiaries have still lower energies. This is evident from a consideration of the absorption coefficients: For air secondaries, 0.32 cm^{-1} Pb (calculated later); for aluminum secondaries, 0.7 cm^{-1} Pb (also obtained later). Hence, the absorption coefficient of the lead secondaries is much greater and the corresponding energy is much smaller than the energy of light element secondaries. Hence only a very small number of these tertiaries get out of the lead. These are probably absorbed in the counter walls or in the steel cylinder which shields the counters from electrical disturbances. Hence they do not affect the count.

An experiment was performed to test the assumption that tertiary particles are produced by light element secondaries. For this purpose a block of aluminum 15.5 cm thick, 13 cm wide and 36 cm long was substituted for the lead block in Fig. 2. This thickness of aluminum is sufficient to absorb all the air secondaries. Also it replaces them with the equilibrium amount of aluminum secondaries.

Runs were made with lead scatterers of various thicknesses, with and without the heavy aluminum block. Sample results are shown in Table II. The increase with the aluminum block over the

TABLE II. *Counting rate with and without aluminum block with various thicknesses.*

LEAD THICKNESS	COUNTING RATE WITH Al BLOCK	WITHOUT Al BLOCK
0.32 cm	10.7 ±0.3	7.5 ±0.6
0.47 cm	14.9 ±0.8	9.2 ±0.7
0.63 cm	13.6 ±0.7	11.5 ±0.7
1.9 cm	10.4 ±0.4	8.1 ±0.6

counters indicates a higher equilibrium value of secondaries from aluminum than from the materials of the roof and the air ordinarily above the counters. It is also possible that aluminum secondaries are more efficient in producing lead tertiaries than air secondaries are, or a combination of the two processes may be the correct explanation.

It will be noted that the counting rate has increased in Table II. This change is due to a change in the counters themselves. From time to time during the course of these experiments, it was found necessary to change the gas in the counters and hence to change their counting rate.

The sources of error, other than that due to statistical fluctuations, are those generally found with Geiger counters and coincidence circuits. One source of error is variation in the counting rate of the counters. The causes of any such variation are usually voltage fluctuations in the high tension and leakage at the condenser-high resistance coupling to the first tube. This latter was minimized even for adverse weather conditions by coating with cerosin, a wax with high resistance to surface leakage. The high tension is taken from a rectifier whose a.c. input is regulated with a voltage regulator. The output voltage was constant to ± 15 volts as checked by a 3 megohm leak and a milliammeter over a long period. This voltage fluctuation is not sufficient to alter appreciably the counting rate.

The next source of error is due to the fact that the triple coincidence selector does not function perfectly. Changes in the efficiency of the circuit due to plate voltage fluctuations were reduced by floating the B battery with a rectifier so that no current was drawn out of the battery. Filament battery voltages were also kept within restricted ranges. However, there might have been some variation in the screen voltage since the current to the screens was not balanced out.

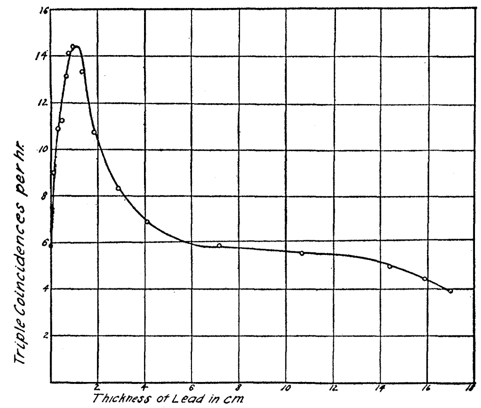


FIG. 3. Absorption-in-lead curve for aluminum secondaries.

Finally, the apparatus was checked from time to time for long period fluctuations by observing the chance count. This chance count over such periods was found to be constant within the statistical error of the rates obtained in the experiment. Hence, we conclude that long period fluctuations are negligible compared to the statistical error. However, there are probably short period fluctuations which are at least as great as the statistical fluctuation due to a finite count.

The thickness of the lead scatterer was varied with the aluminum block over the top counter. The results are plotted in the curve of Fig. 3. It is interesting to note that the curve shows some evidence of a small second maximum. This second rise in the curve occurs at large thicknesses of lead. This doubtful maximum is in accord with the results of Ackemann[4] and of Hummel[5] with two horizontal counters arranged side by side. However, their maxima are much more pronounced. This difference indicates that the particles causing this second increase are in the main uncharged. For if the particles are uncharged, the top counter of the apparatus would not be set off unless a charged particle was ejected from the counter walls. However, in the arrangement of Ackemann and Hummel both charged and uncharged particles can eject charged lead tertiaries into their two counters to produce coincidences.

There has been some indication of the presence of uncharged secondaries in other work. This point we discuss later. The character of the particles producing this second maximum is being investigated.

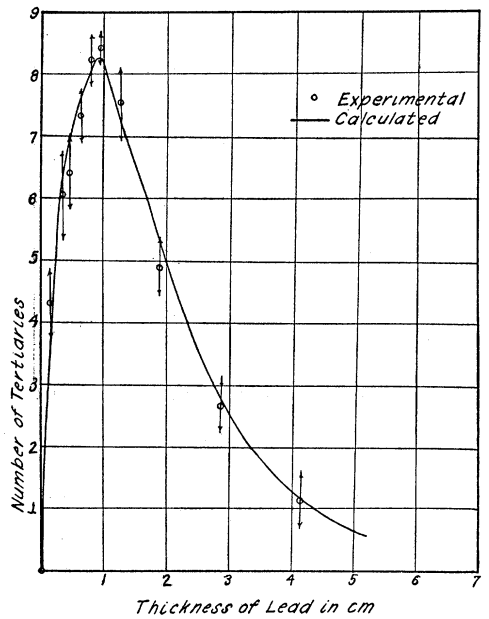


FIG. 4. Calculated absorption curve for aluminum secondaries with experimental points plotted.

From the data of Fig. 3 by means of Eq. (1) we can calculate the absorption coefficients. The absorption coefficient of the lead tertiaries produced by the aluminum secondaries is found to be 2.0 cm^{-1} Pb. The absorption coefficient of the aluminum secondaries in the lead is 0.7 cm^{-1} Pb. The curve obtained from these two calculated absorption coefficients is shown in Fig. 4. The experimental values are plotted on this curve as circles and the statistical errors as the length of the vertical lines through the circles.

Funfer[2] and Rossi[3] have done the most extensive work with Geiger counters on absorption of cosmic-ray particles. Funfer's arrangement is that of Fig. 1 and Rossi's is shown in schematic diagram in Fig. 5. Rossi's curve for the variation of the triple coincidence count with the thickness of S does not agree with Funfer's curve. However, in Rossi's arrangement it is evident that pairs of particles at small angles may produce triple coincidences. This difference is partly due to the bottom counter being twice the size of the other two counters. An example of this is shown in the two ray paths drawn dotted in the figure.

In Fig. 6 Rossi's and Funfer's curves are given and the difference is plotted as the dotted curve.

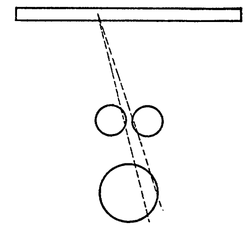


FIG. 5. Rossi's arrangement for investigating air secondaries.

These two curves are reduced to a common basis by considering their respective chance counts, which are a criterion for the sensitivity of the apparatus. Rossi's chance count is approximately twice Funfer's so the ordinate scale of Rossi is made twice that of Funfer. This amounts to plotting the two curves as fractions of the chance counts and the difference curve is obtained in the same way. This difference is due partly to the above property of Rossi's apparatus and partly to the fact that he had heavy blocks of lead protecting the counters at the sides and bottom. These blocks of lead should produce an increase similar to the dotted curve. In fact, Funfer has placed heavy lead blocks at the sides of and beneath his counters and found a very similar increase of the counting rate over that with no protecting blocks. The difference between Rossi's and Funfer's curves is no doubt due to the presence of the heavy lead blocks in Rossi's experiments. Therefore, we have computed the absorption coefficients from Funfer's curve. The

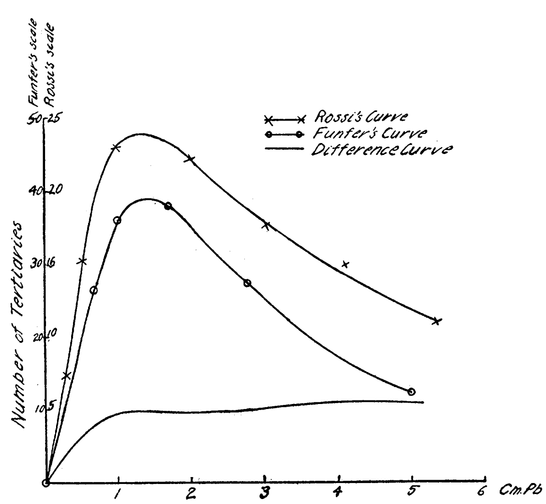


FIG. 6. Rossi's and Funfer's experimental results.

absorption coefficient of air secondaries is found to be 0.32 cm^{-1} Pb, and the absorption coefficient of the lead tertiaries produced by these secondaries is found to be 1.18 cm^{-1} Pb. The values of these coefficients found in our previous paper were 0.5 cm^{-1} Pb for the secondaries and 2.58 cm^{-1} Pb for their tertiaries. This difference is probably due to the fact that there was a heavy roof over our apparatus composed of an inch of tile, 4 inches of concrete and a ceiling. Hence, most of the secondaries probably came from the materials of the roof instead of the air.

The comparison between the absorption coefficients obtained from the data presented here and those obtained from Rossi's and Funfer's data is interesting. The secondaries produced in the aluminum evidently have a lower energy than the air secondaries in Rossi's and Funfer's experiments. This follows from the fact that μ_s for aluminum, 0.7, is greater than for air, 0.32. The comparison is made with Rossi's and Funfer's results for air instead of our previous results on account of the error due to the heavy roof over our apparatus. We see also that the absorption coefficient of the tertiaries from aluminum secondaries, 2.0 cm^{-1} Pb, is greater than that for tertiaries produced by air secondaries, 1.18 cm^{-1} Pb.

The particles which produce this effect are charged particles according to Johnson.[8] He draws this conclusion from a study of the counting rates with the lead scatterer just below and just above the top counter. If there are any uncharged particles ejecting showers of particles from the lead they would not produce triple coincidences with the lead in the first position since the uncharged particle could not actuate the top counter. If any uncharged particles are present the count with the lead above the top counter should therefore be greater than the count with the lead below it.

Johnson found such an increase. However, he maintains that a correction must be applied to the count with lead above the top counter. With no lead present he assumes all the triple coincidences to be caused by showers created in the material of the top counter. These particles would be absorbed with the lead below the top counter and unaffected with the lead above the top counter. Therefore, he subtracts the number of coincidences with no lead present from the number with the lead above the top counter. Then he finds the counting rate with lead above the top counter slightly greater than the rate with the lead below the top counter.

It seems probable that some of the coincidences with no lead present are due to showers from the air and any other materials above the counter. Such shower particles would be absorbed equally with the lead in either position.

Johnson's work has been repeated using also a third position of the lead, just above the bottom counter. This position gives another value of the scattering angle and effective area of the lead plate. The three positions of the lead are shown in Fig. 7 and the results in Table III.

TABLE III. *Counting rate for different positions of S.*

Position of S	Total count	Total time	Rate
1. Just above bottom counters	330	37.2 hr.	8.87 ±0.32
2. Just below top counter	479	49.6 hr.	9.66 ±0.30
3. Just above top counter	262	18.0 hr.	14.5 ±0.58

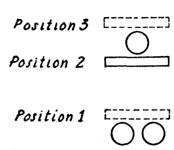


FIG. 7.

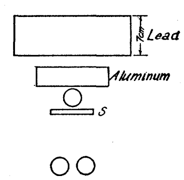


FIG. 8.

FIG. 7. Arrangement for investigating non-ionizing primaries which cause showers.

FIG. 8. Arrangement for investigating hardness of primaries which produce tertiaries.

There is a substantial increase in the counting rate with the lead just above the top counter as Johnson found. This increase might be ascribed to the fact that the scattering angle is decreased when the lead is moved from beneath to above the top counter. However, the scattering angle was increased even more by moving the lead from position 1 to position 2 and the count was not affected. Hence this was probably not the cause of the increase.

Also there might be an increase due to the edges of the lead plate being effective in position 3 and not in position 2. However, the edges are effective also in position 1 and there is no increase; so this is probably not the cause of the

[8] T. H. Johnson, Phys. Rev. **45**, 581 (1934).

increase. Hence, it seems probable that there are non-ionizing particles causing some of the showers. This causes the large increases in counting when the lead is moved from position 2 to position 3.

Recent work by Gilbert[9] and Johnson[8] has shown that the production of tertiary particles increases greatly at high altitudes. Johnson compares the intensity of tertiaries (denoted showers by Johnson and Gilbert) at two high altitudes. He finds the ratio of these two intensities the same as the ratio of the intensities of the soft corpuscular component of the primary radiation at the same altitudes. He concludes therefore that the soft corpuscular component is the principal source of showers.

In order to test this conclusion the arrangement of Fig. 8 was employed. Here, the heavy lead block cuts down the intensity of the soft, corpuscular component and does not appreciably affect the intensity of the penetrating cosmic particles. If the primary rays causing the effect were the penetrating component, then they would knock secondaries from the aluminum block as before. These secondaries should have almost the same intensity as when the heavy lead block was not there. This follows since the intensity of the primary penetrating rays is only slightly reduced by 7 cm of lead. Then, these aluminum secondaries should pass through the top counter and eject tertiaries from S into the bottom counters.

On the other hand, if the primary particles causing this effect are the soft corpuscular ones, the 7 cm of lead should cut out about $\frac{1}{3}$ of the primary shower-producing rays. These rays should build up aluminum secondaries to an equilibrium value as the thickness of the aluminum is increased. These aluminum secondaries will produce tertiaries in the scatterer S.

However, in this experiment it was found that the triple coincidence count increased with the thickness of the aluminum to a maximum and then decreased with greater thicknesses to the chance count.

Table IV gives the results obtained in several different cases.

It is easily seen from these results that the increase is due both to the presence of the aluminum and the scatterer. Hence we conclude that the secondary particles from the aluminum are producing showers in the lead scatterer. It will also be noted that the increased count is considerably less than the count without the lead block present.

[9] C. W. Gilbert, Proc. Roy. Soc. **A144**, 559 (1934).

TABLE IV. *Counting rates for different thicknesses of blocks.*

Thickness of top Pb block	Thickness of Al block	Thickness of Pb scatterer	Rate
7	3.8	0.0	16.8±0.6
7	3.8	0.63	18.3±0.6
7	0.0	0.63	16.8±0.6
0	3.8	0.63	27.0±0.8

Next, the variation of this triple coincidence count with the thickness of aluminum was obtained. The results are shown in Table V.

It follows from these results and the results of Table IV that the primary particles causing the showers are probably even softer than the soft corpuscular component of Johnson. We see this from a comparison of Table V with Fig. 3. In Fig. 3 the increase over the chance count for the 0.63 cm Pb scatterer and the 15.5 cm aluminum block is about 7 or a little over 100 percent of the chance count. In Table V, placing the 7 cm of Pb over the 15.5 cm aluminum block completely absorbs the effect so that we merely obtain the chance count. Thus the particles which excited secondaries in the aluminum in the first case being completely absorbed in 7 cm Pb, must be softer than Johnson's corpuscular component which would only be about 33 percent absorbed.

The manner in which the number of coincidences in Table V increases with the thickness of Al and then decreases is difficult to explain. We might explain this decrease of the effect with increased thickness of aluminum in the following way. The aluminum first builds up secondaries to produce showers in the lead and then with increased thicknesses begins to absorb out the primary particles which excite the

TABLE V. *Increase of counting rate due to aluminum block.*

Thickness of top Pb block	Thickness of Al block	Thickness of Pb scatterer	Rate	Increase due to Al
7	0.0	0.63	16.8±0.6	—
7	1.27	0.63	19.9±0.7	3.1
7	2.54	0.63	20.9±0.9	4.1
7	3.8	0.63	18.3±0.6	1.5
7	7.6	0.63	16.4±0.6	−0.4
7	15.5	0.63	16.6±0.7	−0.2

aluminum secondaries. But the primary particles would have to be exceptionally soft to be absorbed by 8 cm of aluminum, and so this explanation contradicts the fact that they were penetrating enough to go through 7 cm of Pb.

Another explanation is that these particles are some kind of radiation excited in the lead block. It has been shown that lead secondaries are not effective in the usual experiments. However, these particles from the lead might be of a non-ionizing nature. Then, they would not be effective in the previous experiment. In this case the non-ionizing particles would have an opportunity to excite ionizing particles in the aluminum. Then, these particles could produce the usual showers in the lead scatterer. This explanation seems rather complex; but it is the only one evident at present.

The non-ionizing character of the rays from the lead block was investigated in the usual way. An aluminum block 2.54 cm thick, was first placed above the top counter and then below it. The same scatterer, a 0.63 cm Pb sheet, was used in both cases. The two counts were: 18.1 ± 0.4 with the aluminum above the top counter and 14.5 ± 0.4 with the aluminum below the top counter which is equal to the chance count. Thus the rays from the lead do not affect the top counter, but they produce rays in the aluminum which do effect it. The rays from the lead must therefore be non-ionizing rays, possibly neutrons.

I wish to express my sincere gratitude to Professor H. A. Wilson for his kindly interest in this work and for the many helpful interviews with him during its progress.

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The Deep Configurations of Cobalt

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The energy matrix of electrostatic and magnetic spin-orbit interaction is set up for d^7s^2, d^8s and d^9, taking into account the mutual interactions of these configurations. The secular equations are fitted to the deep configurations of Co I, separately, by selecting suitable values for the interaction parameters. The uncertainty existing concerning the assignments of a^2D, a^2G and b^2D is removed. The g-factors for the Zeeman effect in intermediate coupling are calculated for comparison with experimental values presented in the following paper. The mutual interactions of $3d^84s$ with $3d^74s^2$ and $3d^9$ are found to be relatively insignificant. The secular equations are fitted to $3d^74s^2$ and $3d^9$ together, tentatively, in order to observe the effect of mutual interaction upon the values of certain terms which have not yet been discovered, and upon the g-factors. The interaction parameters are compared with those of the deep configurations of Ni I.

THE deep electron configurations of the cobalt atom are $3d^74s^2$, $3d^84s$ and $3d^9$, according to Hund's theory. The most extensive classification of the Co I spectrum has been given by Catalán,[1] who has assigned the deep terms to $3d^74s^2$ and $3d^84s$. The assignments of the quartet and doublet F and P terms, based upon the intensities of their numerous combinations with terms which belong to the intermediate configurations $3d^74s4p$ and $3d^84p$, are certain. The combinations of the other deep terms are both few in number and weak. The assignments of a^2D to $3d^74s^2$, and a^2G and b^2D to $3d^84s$ are tentative. This appears to have been overlooked by Kayser and Konen,[2] who have taken these assignments as assured. Bacher and Goudsmit[3] have assigned a^2G definitely and a^2D tentatively to $3d^74s^2$, and b^2D definitely to $3d^9$.

Such uncertainty concerning the assignment of multiplets is by no means uncommon where two or more configurations overlap. The theoretical study of the configurations d^7s^2, d^8s and d^9, which is presented in this paper, shows that it is possible to remove the uncertainty when the departure from LS coupling is not extreme.

[1] Catalán, An. soc. espan. fis. y quim. **27**, 832 (1929).

[2] Kayser and Konen, *Handbuch der Spektroscopie*, VIII, p. 501.

[3] Bacher and Goudsmit, *Atomic Energy States*, p. 150.